

# New Constraints on Dark Matter from CMS and ATLAS data

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## Abstract

Constraints on dark matter from the first CMS and ATLAS SUSY searches are investigated. It is shown that within the minimal supergravity model, the early search for supersymmetry at the LHC has depleted a large portion of the signature space in dark matter direct detection experiments. In particular, the prospects for detecting signals of dark matter in the XENON and CDMS experiments are significantly affected in the low neutralino mass region. Here the relic density of dark matter typically arises from slepton coannihilations in the early universe. In contrast, it is found that the CMS and ATLAS analyses leave untouched the Higgs pole and the Hyperbolic Branch/Focus Point regions, which are now being probed by the most recent XENON results. Analysis is also done for supergravity models with non-universal soft breaking where one finds that a part of the dark matter signature space depleted by the CMS and ATLAS cuts in the minimal SUGRA case is repopulated. Thus, observation of dark matter in the LHC depleted region of minimal supergravity may indicate non-universalities in soft breaking.

**Keywords:** Dark matter, XENON, CDMS, CMS, ATLAS, SUGRA

## I. INTRODUCTION

CMS and ATLAS have recently reported their first results for supersymmetry searches [1–3] and have put new constraints on the parameter space of the  $\mathcal{N} = 1$  supergravity unified model [4] which, with universal boundary conditions on the soft breaking parameters at the unification scale, is the model mSUGRA [4–6]. In a subsequent work [7], the implications of the CMS and ATLAS searches on the mSUGRA parameter space was analyzed in the context of indirect constraints from LEP and Tevatron searches, from the Brookhaven  $g_\mu - 2$  experiment, from FCNC constraints in B-physics, i.e.,  $b \rightarrow s\gamma$  and  $B_s^0 \rightarrow \mu^+\mu^-$  and from WMAP. Some related works have appeared in [8].

In this work we analyze the impact of the first results from CMS and ATLAS SUSY searches on the direct detection of dark matter [9, 10]. It is found that the LHC results have a large impact on the signature space available for the low mass slepton coannihilation region, depleting a significant region where direct detection experiments are sensitive to detecting a signal. Thus, we explore the effect of the recent LHC data on the prospects for directly detecting cold dark matter in experiments such as XENON and CDMS in supergravity unified models. We will discuss both minimal supergravity models, and SUGRA models with non-universal soft breaking terms at the grand unification scale.

For completeness, we begin with a brief summary of the independent parameters generated by softly broken supergravity theories which are needed to test such models at colliders and in dark matter experiments. Comprehensive reviews can be found in [11–13]. The conditions under which the soft breaking in the minimal supergravity model are derived are summarized as follows: (i) supersymmetry is broken through a super Higgs effect giving mass to the gravitino through the presence of a hidden sector (singlet); (ii) the hidden and the visible interact only gravitationally; (iii) the Kähler potential is generation independent; (iv) the gauge kinetic function is minimally linear in the hidden sector singlet. This then gives rise to soft terms of the form [4]

$$\begin{aligned} \mathcal{L}_{soft} = & -\frac{1}{2}(M_a\lambda^a\lambda^a + h.c.) - m_\alpha^2 C^{*\alpha}C^\alpha \\ & - \left( \frac{1}{6}A_{\alpha\beta\gamma}Y_{\alpha\beta\gamma}C^\alpha C^\beta C^\gamma + B_0\mu_0 H_1 H_2 + h.c. \right), \end{aligned} \quad (1)$$

where  $\lambda^a$  are the gauginos,  $H_{i=1,2}$  are Higgs doublets, and  $C^\alpha$  are the slepton, squark and Higgs fields of the minimal supersymmetric standard model. For the case of universal

boundary conditions at the unification (GUT) scale,  $m_\alpha = m_0$  is the universal scalar mass,  $M_a = m_{1/2}$  is the universal gaugino mass,  $A_{\alpha\beta\gamma} = A_0$  is the universal trilinear coupling, and  $B_0\mu_0$  is the bilinear coupling where  $\mu_0$  is the Higgs mixing parameter that enters the superpotential in the form  $\mu_0 H_1 H_2$  (all at the GUT scale). Thus, the minimal supergravity models are specified by the following set of GUT scale parameters  $(m_0, m_{1/2}, A_0, B_0, \mu_0)$ . The renormalization group improved scalar potential at the electroweak symmetry breaking scale  $Q$  is given by

$$\begin{aligned}
V &= m_1^2 |H_1|^2 + m_2^2 |H_2|^2 - m_3^2 (H_1 H_2 + h.c.) \\
&\quad + \frac{(g_2^2 + g_Y^2)}{8} (|H_1|^2 - |H_2|^2)^2 + \Delta V_1, \\
\Delta V_1 &= \frac{1}{64\pi^2} \sum_a (-1)^{2s_a} (2s_a + 1) M_a^4 \left[ \ln \frac{M_a^2}{Q^2} - \frac{3}{2} \right], \tag{2}
\end{aligned}$$

where the term  $\Delta V_1$  is the one loop correction to the effective potential in the MSSM [15–17], and  $s_a$  is the spin of particle  $a$ . The gauge couplings are subject to boundary conditions at the unification scale  $\alpha_2(0) = \alpha_G = \frac{5}{3}\alpha_Y(0)$ , while if the soft parameters are universal one has  $m_i^2(0) = m_0^2 + \mu_0^2$ ,  $i = 1, 2$ ; and  $m_3^2(0) = -B_0\mu_0$ . The breaking of electroweak symmetry occurs when (a) the determinant of the Higgs mass<sup>2</sup> matrix turns negative and (b) the potential is bounded from below; i.e. (a)  $m_1^2 m_2^2 - m_3^4 < 0$ , and (b)  $m_1^2 + m_2^2 - 2|m_3^2| > 0$ . Minimization of the potential then yields the following relations (I)  $M_Z^2 = 2(\mu_1^2 - \mu_2^2 \tan^2 \beta)(\tan^2 \beta - 1)^{-1}$  and (II)  $\sin 2\beta = 2m_3^2(\mu_1^2 + \mu_2^2)^{-1}$ , where  $\mu_i^2 = m_i^2 + \Sigma_i$ , where  $\Sigma_i$  are the loop corrections [16, 17]. Here  $\tan \beta = v_2/v_1$  is the ratio of the Higgs VEVs. (I) can be used to fix  $\mu$  using the experimental value of  $M_Z$ , and the constraint (II) can be used to eliminate  $B_0$  in favor of  $\tan \beta$ . The supergravity model at low energy can then be parametrized by [6]

$$m_0, \quad m_{1/2}, \quad A_0, \quad \tan \beta, \quad \text{sign}(\mu). \tag{3}$$

After specifying the high scale soft breaking parameters, one implements renormalization group analysis (see [18] for the two loop analysis) and is then able to predict all 32 sparticles masses as well as their couplings and interactions. The full analysis can be done via [19].

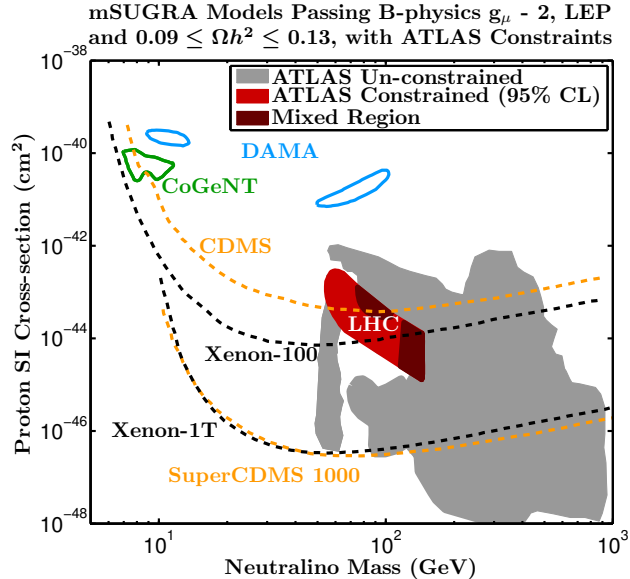


FIG. 1: (color online) A plot of spin independent neutralino-proton cross section vs neutralino mass for mSUGRA under experimental constraints. The search for supersymmetry at LHC with  $35 \text{ pb}^{-1}$  luminosity has excluded a significant number of models in this signature space which are marked by red color. In the red region, all the models in our scans have been constrained by the ATLAS search, while in the mixed region (maroon), about 60% of the models in our scans are constrained by the ATLAS search. We also display the present CDMS [10] and XENON-100 [9] curves as well as the future projected experimental curves [20, 21].

## II. ATLAS AND CMS CONSTRAINTS ON DARK MATTER DIRECT DETECTION IN MINIMAL SUPERGRAVITY

We discuss now the implications of ATLAS and CMS results on dark matter. For a sample of works on dark matter and LHC, we refer the reader to [14]. SUGRA models predict a dark matter candidate which over much of the parameter space is the lightest neutralino, the lightest (R-parity odd) superpartner (LSP). The LSPs are traveling with non relativistic speed order  $0.001c$  in the galactic halo. This then translates into the fact that their momentum transfer is very small (order 100 MeV for LSP masses of order 100 GeV) in collisions with nuclei in a terrestrial detector. As such, the relevant interactions for the direct detection of LSP dark matter is calculated in the limit of zero momentum transfer

in collisions with nuclei. For SUGRA models the interaction Lagrangian is given by [22, 23]

$$\begin{aligned}\mathcal{L} = & \bar{\chi}\gamma^\mu\gamma^5\chi\bar{q}_i\gamma_\mu(\alpha_{1i} + \alpha_{2i}\gamma^5)q_i + \alpha_{3i}\bar{\chi}\chi\bar{q}_iq_i + \\ & \alpha_{4i}\bar{\chi}\gamma^5\chi\bar{q}_i\gamma^5q_i + \alpha_{5i}\bar{\chi}\chi\bar{q}_i\gamma^5q_i + \alpha_{6i}\bar{\chi}\gamma^5\chi\bar{q}_iq_i .\end{aligned}\quad (4)$$

The spin independent (SI) cross section for neutralinos scattering elastically off target nuclei is mostly governed by the operator  $\alpha_{3i}\bar{\chi}\chi\bar{q}_iq_i$ . For heavy nucleus targets, the SI cross section add up coherently

$$\sigma_{\chi T} = \frac{4\mu_{\chi T}^2}{\pi}(Zf_p + (A - Z)f_n)^2 , \quad (5)$$

where  $\mu_{\chi T}$  is the reduced mass of the neutralino and the target system, and  $(Z, A)$  are the atomic (number, mass) of the nucleus. The interactions between the LSP and the target nuclei occur dominantly via  $t$ -channel CP-even Higgs exchange, and  $s$ -channel squark exchange. The relevant interactions are given in terms of

$$f_{p/n} = \sum_{q=u,d,s} f_{T_q}^{(p/n)} a_q \frac{m_{p/n}}{m_q} + \frac{2}{27} f_{TG}^{(p/n)} \sum_{q=c,b,t} a_q \frac{m_{p/n}}{m_q} . \quad (6)$$

Here  $f_{T_u}^{(p/n)}$ ,  $f_{T_d}^{(p/n)}$ ,  $f_{T_s}^{(p/n)}$  are the nucleon parameters which can be obtained from the measurements of the pion-nucleon sigma term, and  $f_{TG}^{(p/n)} \equiv 1 - f_{T_u}^{(p/n)} - f_{T_d}^{(p/n)} - f_{T_s}^{(p/n)}$ . Numerical values and further details are given in, for example, in Ref. [24]. The spin independent cross section depends sensitively on LSP neutralino decomposition in terms of its Bino, Wino and Higgsino eigen components ( $(\tilde{B}, \tilde{W}^3) \equiv (\lambda_Y, \lambda^3)$ )

$$\chi \equiv \chi_1^0 = n_{11}\tilde{B} + n_{12}\tilde{W}^3 + n_{13}\tilde{H}_1 + n_{14}\tilde{H}_2 . \quad (7)$$

The relevant couplings that enter in the spin independent cross section are [22, 23]

$$\begin{aligned}a_q \equiv a_{3i} = & -\frac{1}{2(m_{1i}^2 - m_\chi^2)} \Re[(X_i)(Y_i)^*] - \frac{1}{2(m_{2i}^2 - m_\chi^2)} \Re[(W_i)(V_i)^*] \\ & - \frac{g_2 m_q}{4m_W B} \left[ \Re(\delta_1[g_2 n_{12} - g_Y n_{11}]) DC \left( -\frac{1}{m_H^2} + \frac{1}{m_h^2} \right) \right. \\ & \left. + \Re(\delta_2[g_2 n_{12} - g_Y n_{11}]) \left( \frac{D^2}{m_h^2} + \frac{C^2}{m_H^2} \right) \right] .\end{aligned}\quad (8)$$

Here the various quantities  $X_i, Y_i, W_i$  etc are defined in [22, 23], where the full forms of  $a_q$  can also be found. The first two terms arise from squark  $(m_{1i}, m_{2i})$  exchange while the remaining terms arise from Higgs exchange which are almost always dominant in the models we discuss. The parameters  $\delta_{1,2}$  depend on eigen components of the LSP wave function and

$B, C, D$  depend on VEVs of the Higgs fields and the Higgs mixing parameter  $\alpha$  and are given by

$$\text{for u quarks : } \delta_1 = n_{13} \quad \delta_2 = n_{14} \quad B = \sin \beta \quad C = \sin \alpha \quad D = \cos \alpha \quad (9)$$

$$\text{for d quarks : } \delta_1 = n_{14} \quad \delta_2 = -n_{13} \quad B = \cos \beta \quad C = \cos \alpha \quad D = -\sin \alpha . \quad (10)$$

In Fig.(1) we give the spin independent cross sections vs the neutralino mass after experimental constraints are applied (discussed in Sec.(IV)) as well as constraints from the LHC SUSY searches [7]. We describe the simulations further in what follows. Also shown are the XENON-100 [9], CDMS II [10] and projected XENON and SuperCDMS limits for comparison [20, 21]. The direct mapping of the parameter space constrained by the recent CMS and ATLAS searches is substantial in the spin independent scattering cross section - dark matter mass plane. This is achieved by simulating the LHC SUSY production of the models and SM backgrounds under CMS and ATLAS cuts. We extend their results by considering a larger class of models over the parameter space relevant to early SUSY searches. In Fig.(1), we identify the region in this plane that the LHC data constrains. We will see that this corresponds to the low mass branch of the slepton coannihilation region, defined by  $(m_{\tilde{l}} - m_{\tilde{\chi}_1^0})/m_{\tilde{\chi}_1^0} \lesssim 0.2$ . Thus, observation of dark matter in the LHC depleted region may indicate the presence of nonuniversalities. We discuss now the CMS and ATLAS analyses, and their generalizations and implications in more detail.

### III. LHC ANALYSIS

Here, we analyze the nature of the NLSP in the regions of the parameter space depleted by the CMS and ATLAS results as well as the SUSY event rates in the region that would be accessible to both the dark matter direct detection experiments and the LHC in the next rounds of data. As evident from the results of [1–3] the 0 lepton ATLAS analysis is the most stringent, so we mainly focus on this search in our analysis, but we have still checked these models with the 1 lepton ATLAS search and the CMS  $\alpha_T$  jet search. We discuss in detail the 0 lepton ATLAS search only; the reader is directed to [1, 2] for a more detailed discussion on the other LHC SUSY searches.

We follow the preselection requirements that ATLAS reports in [3, 25]. Jet candidates must have  $p_T > 20$  GeV and  $|\eta| < 4.9$  and electron candidates must have  $p_T > 10$  GeV

and  $|\eta| < 2.47$ . Events are vetoed if a “medium” electron [25] is in the electromagnetic calorimeter transition region,  $1.37 < |\eta| < 1.52$ . Muon candidates must have  $p_T > 10$  GeV and  $|\eta| < 2.4$ . Further, jet candidates are discarded if they are within  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.2$  of an electron. For the analysis, the (reconstructed) missing energy,  $\cancel{E}_T$ , for an event is the negated vector sum of the  $p_T$  of all the jet and lepton candidates.

The analysis is made up of 4 regions, “A”, “B”, “C” and “D”, each having 0 lepton candidates. When referring to different cuts in these regions we define cuts on the “selected” jets to mean that the “selected” jet candidate has  $|\eta| < 2.5$  and the bare minimum number of jets in this region must satisfy the requirement. For regions A and B “selected” jets refers to the first two hardest jets in the  $|\eta| < 2.5$  region and for regions C and D “selected” jets refers to the first three hardest jets in the  $|\eta| < 2.5$  region. Events are required to have  $\cancel{E}_T > 100$  GeV and the selected jets must each have  $p_T > 40$  GeV with the hardest jet  $p_T > 120$  GeV. Further, events are rejected if the missing energy points along the same direction as any of the selected jets, i.e. we require  $\Delta\phi(j_i, \cancel{E}_T) > 0.4$ , where  $i$  is over the “selected” jets. Region A requires events to have  $\cancel{E}_T > 0.3m_{\text{eff}}$  with  $m_{\text{eff}} > 500$  GeV and regions C and D both require events to have  $\cancel{E}_T > 0.25m_{\text{eff}}$  with region C requiring  $m_{\text{eff}} > 500$  GeV and region D requiring  $m_{\text{eff}} > 1$  TeV. In this case  $m_{\text{eff}}$  is defined to be the scalar sum of the missing energy and the  $p_T$  of the “selected” jets. As in the analysis of [7] we do not apply the cut for region B, i.e.  $m_{T2} > 300$  GeV, since the models constrained in this region are already constrained in region D [26].

For our analysis, we use the simulated SM background of [27] which was generated with **MadGraph 4.4** [28] for parton level processes, **Pythia 6.4** [29] for hadronization and **PGS-4** [30] for detector simulation. A more thorough discussion on the details of this background can be found in [27, 31] and Ref. 1 of [8], (see also [32–34] for discussions on SM background for  $2 \rightarrow N$  processes). After applying the LHC SUSY analysis to our SM background we are able to reproduce their reported standard model Monte Carlo results.

#### IV. RESULT OF DARK MATTER ANALYSIS WITH CMS-ATLAS CONSTRAINTS

We discuss now the implications of the data from CMS and ATLAS on dark matter. To this end we first carry out a survey of the mSUGRA parameter space as follows:  $m_0 \in (10, 4000)$  GeV,  $m_{1/2} \in (10, 2000)$  GeV,  $A_0 \in (-10, 10)m_0$ ,  $\tan\beta \in (1, 60)$ . Performing a general survey of the mSUGRA model space we simulate the models that satisfy radiative electroweak symmetry breaking (REWSB) as well as direct and indirect experimental constraints including sparticle mass limits, B-physics constraints, and constraints from  $g_\mu - 2$ . We further require that the relic density be within the observed WMAP limit [35],  $0.0896 < \Omega_\chi h^2 < 0.1344$ . These indirect constraints were calculated using **MicrOmegas** [24], with the Standard Model contribution in the  $\mathcal{B}r(b \rightarrow s\gamma)$  corrected using the NNLO analysis of Misiak *et al.* [36, 37]. We apply the following “collider/flavor constraints” [38]  $m_h > 93.5$  GeV,  $m_{\tilde{\tau}_1} > 81.9$  GeV,  $m_{\tilde{\chi}_1^\pm} > 103.5$  GeV,  $m_{\tilde{t}_1} > 100$  GeV,  $m_{\tilde{b}_1} > 89$  GeV,  $m_{\tilde{e}_R}, m_{\tilde{e}_L} > 107$  GeV,  $m_{\tilde{\mu}_R}, m_{\tilde{\mu}_L} > 94$  GeV, and  $m_{\tilde{g}} > 400$  GeV, along with  $(-11.4 \times 10^{-10}) \leq \delta(g_\mu - 2) \leq (9.4 \times 10^{-9})$ , see [39],  $\mathcal{B}r(B_s \rightarrow \mu^+ \mu^-) \leq 4.2 \times 10^{-8}$  (90% C.L.) [40], and  $(2.77 \times 10^{-4}) \leq \mathcal{B}r(b \rightarrow s\gamma) \leq (4.37 \times 10^{-4})$  [41].

To investigate the constraints from the LHC SUSY search on the dark matter detection signals, we scanned over 20 million models in the mSUGRA parameter space. After imposing the various experimental constraints as previously discussed, we simulate the models with the ATLAS 0-lepton analysis. It is found that there exists a large portion of the signature space in the spin independent cross section-neutralino plane which is being excluded by the ATLAS 0-lepton search. This excluded region which is marked by red color as shown in Fig.(1) was populated by mSUGRA models before considering the new LHC data. We further divide the excluded region into the red region where all the mSUGRA models scanned are excluded by the LHC data, and the two maroon regions each with about 60% of the models excluded by the LHC. (Note that ATLAS carried out their analysis for a few fixed values of  $\tan\beta$  and  $A_0$  while our analysis allow these to vary.) Next, by considering the NLSP, we find that essentially all of the region that is depleted by the LHC at 95% CL is the low mass region of the slepton coannihilation branch.

This is shown more clearly in Fig.(2) where we display the number of SUSY events vs the neutralino mass for a subset of models in the two panels corresponding to the regions A



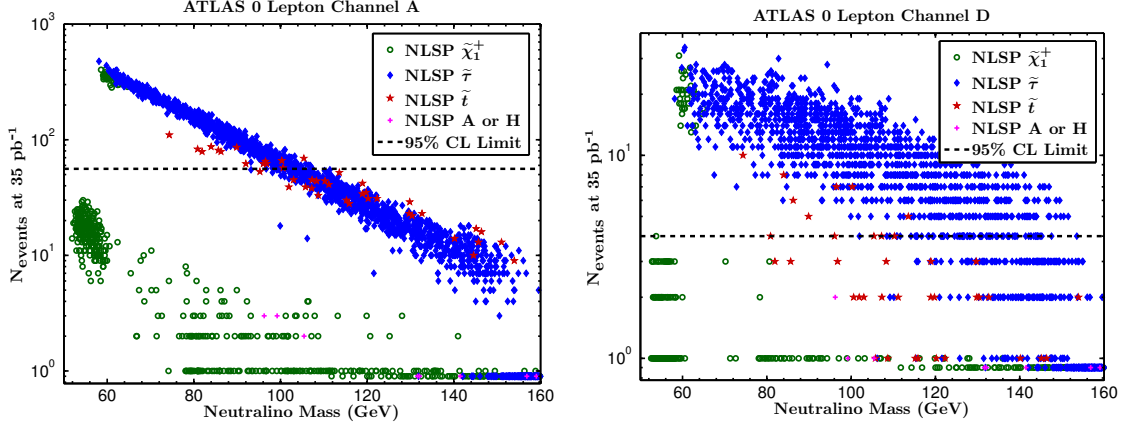


FIG. 2: (color online) Exhibition of the number of SUSY events in the ATLAS 0 lepton analysis and the corresponding NLSPs against the neutralino mass with  $35 \text{ pb}^{-1}$  of integrated luminosity for a subset of models around the LHC excluded region of Fig.(1). Left panel: Region A [3]; Right panel: Region D [3]. The dashed black lines can be viewed as the 95% C.L. limit in each signal region, as they correspond to the event thresholds reported by ATLAS along the the  $m_0 - m_{1/2}$  boundaries [26]. Essentially, the models being eliminated by the ATLAS results (above the dashed black line) are those with the stau as the NLSP.

and D with low neutralino masses. We do not display region C since it gives results similar to region A and we do not display region B since it is subsumed in region D. The dashed black lines in Fig.(2) can be viewed as the 95% C.L. limit in each signal region, as they correspond to the event thresholds reported by ATLAS. Indeed, most of the model points being constrained by the LHC are those where the stau is the NLSP appropriate for the slepton coannihilation branch. Further, very few of the model points are constrained by the ATLAS analysis which lie on the Hyperbolic Branch (HB) (Focus Point region) [42] of REWSB. The NLSP on the HB is mostly the light chargino and from Fig.(1) we find that very few of the chargino NLSP models are currently constrained by the ATLAS analysis.

In contrast, the higher mass HB/FP region is becoming constrained by the XENON data [9]. This effect can be seen in Fig.(3) where we show the  $m_0 - m_{1/2}$  plane for the mSUGRA case denoted by their NLSP where the models on the left panel are constrained by XENON-100 and the models on the right panel are unconstrained by XENON-100.

Thus, we come to the conclusion that the ATLAS constraints are very severe for the

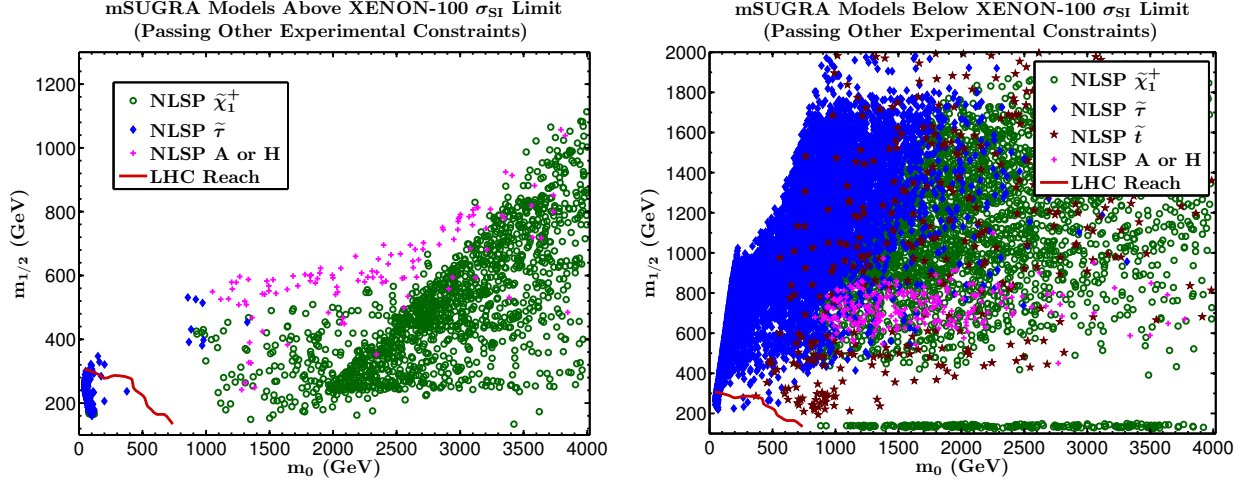


FIG. 3: (color online) Exhibition of models in the  $m_0 - m_{1/2}$  plane denoted by their NLSPs and the ATLAS 0 lepton curve (red) is drawn for comparison (see Fig.(1)). The left panel corresponds to the models that have been constrained by XENON-100 [9] and the right panel corresponds to the models that are unconstrained by XENON-100. All models have the same constraints as Fig.(1). From this analysis we see explicitly that the reported XENON constraints are severe in the larger  $m_0$  region constraining the hyperbolic branch, while the low  $m_0$  region, which are the low mass slepton coannihilation regions, are being constrained by both XENON and the LHC.

low  $m_0$  region, while the XENON constraints are very severe for the large  $m_0$  region as shown. As can be seen from Ref. [7], the region which is now being constrained by XENON corresponds to  $\mu \lesssim 400$  GeV and here the LSP wavefunction has a significant Higgsino component. We add here that bulk region and the higgs pole region (the latter being the horizontal strip of essentially fixed  $m_{1/2} \sim O(100 - 150)$  GeV) remain largely untouched by either experiments.

More generally while the recent XENON analysis [9] has presented plots along with mSUGRA [6] (see Eq. (3)) model points on top of the data – we suggest that the XENON collaboration include the 50 GeV to 65 GeV mass range of mSUGRA in their constraint plots as this is the region where the XENON data shows its greatest present sensitivity (see e.g. Ref. 1 of [8] for this dense region of parameter space; the Higgs pole region mentioned above). We also remark that in the analysis of the spin independent cross section we used the default values of the form factors as given in Ref. [24]. It is well known, the predictions for

the SI cross section are sensitive to the precise knowledge of the form factors and in particular the strange quark form factor. In addition, variations on the order of 5 or larger have been reported in the second reference of [23] and in [24] over a reasonable range of the pion-nucleon sigma term (for which the above form factors depend on). These uncertainties should be kept in mind while interpreting the results of dark matter direct detection experiments on the parameter space of models. Thus, while we have shown in Fig.(3) the regions which lie below and above the reported XENON limits one does need to factor in more generally the uncertainties in the hadronic matrix elements as well as the uncertainties in astrophysical quantities to have a more precise account of the constrained region of parameter space. However, such an analysis goes beyond the scope of this work. Thus our aim here is to emphasize that the sensitivity of the XENON detector is encroaching on a new part of the space of SUGRA models, and it is beginning to provide more stringent constraints on the larger  $m_0$  region for which the Higgsino component of the LSP wavefunction can become significant.

## V. SUGRA MODELS WITH NON-UNIVERSAL BREAKING

The analysis for the mSUGRA case highlighted in Fig.(1) shows a deficit of models after the LHC constraints are applied in the region under the XENON-100 curve in the neutralino mass range of 50 GeV to 100 GeV corresponding to the slepton coannihilation region. While the assumption of universal boundary conditions on soft breaking in supergravity grand unification [4] is the simplest possibility leading to the model mSUGRA, the framework of supergravity unification [4] allows for non-universalities in the soft parameters which occurs generically for several classes of string motivated models (see [43–46]).

Non-universal gaugino masses can arise in two ways (a) from tree level supergravity with a gauge kinetic function dependent on singlets or products of singlets and fields which transform under the gauge groups of the standard model (b) from loop induced gaugino masses dependent on the beta function coefficient for each group. For tree level gaugino masses one has

$$M_a = \frac{1}{2\Re(f_a)} F^I \partial_I f_a .$$

where  $F^I$  are the order parameters of SUSY breaking,  $I$  denotes the hidden sector (singlet)

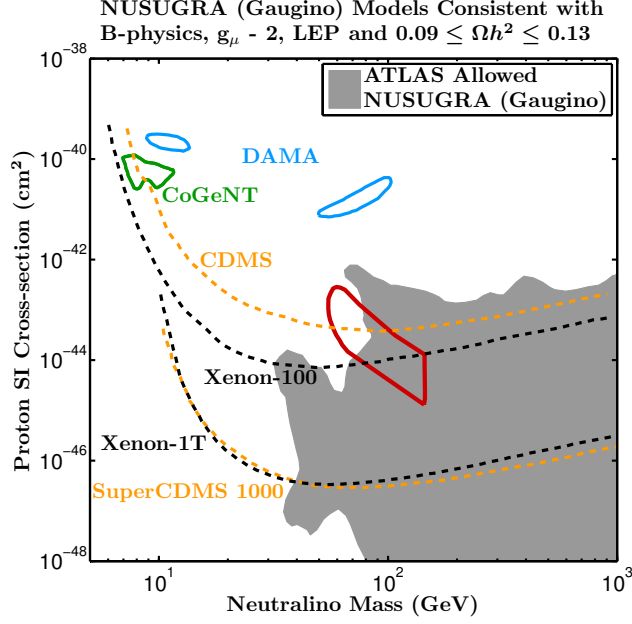


FIG. 4: (color online) Analysis of models with non-universalities in the gaugino masses with the LEP, Tevatron,  $g_\mu = 2$ , FCNC and WMAP constraints. The red contour is the region depleted for mSUGRA by the ATLAS results and is shown for comparison. The random scan does not emphasize the mSUGRA parameter region.

fields responsible for the breaking of SUSY and  $f_a$  is a diagonal gauge kinetic function, where  $a$  is an adjoint index for each gauge group. In addition for loop induced gaugino masses one has [43, 47, 48]

$$M_a^1|_{\text{adj}} = -b_a^0 g_a^2 m_{3/2} + \dots$$

where the higher order terms are given in [48] and the beta function coefficient is given in terms of  $C_a, C_a^i$ ; the quadratic Casimir operators for the gauge group  $G_a$  respectively in the adjoint representation

$$b_a^0 = \frac{1}{16\pi^2} (3C_a - \sum_i C_a^i)$$

Thus we now consider the case of non-universal supergravity (NUSUGRA) models to see if the region depleted in the mSUGRA case can become populated when non-universalities are included. Here we will keep the analysis rather general and parametrize the non-universalities as in the gaugino masses which can be sourced from tree level supergravity, from loop induced

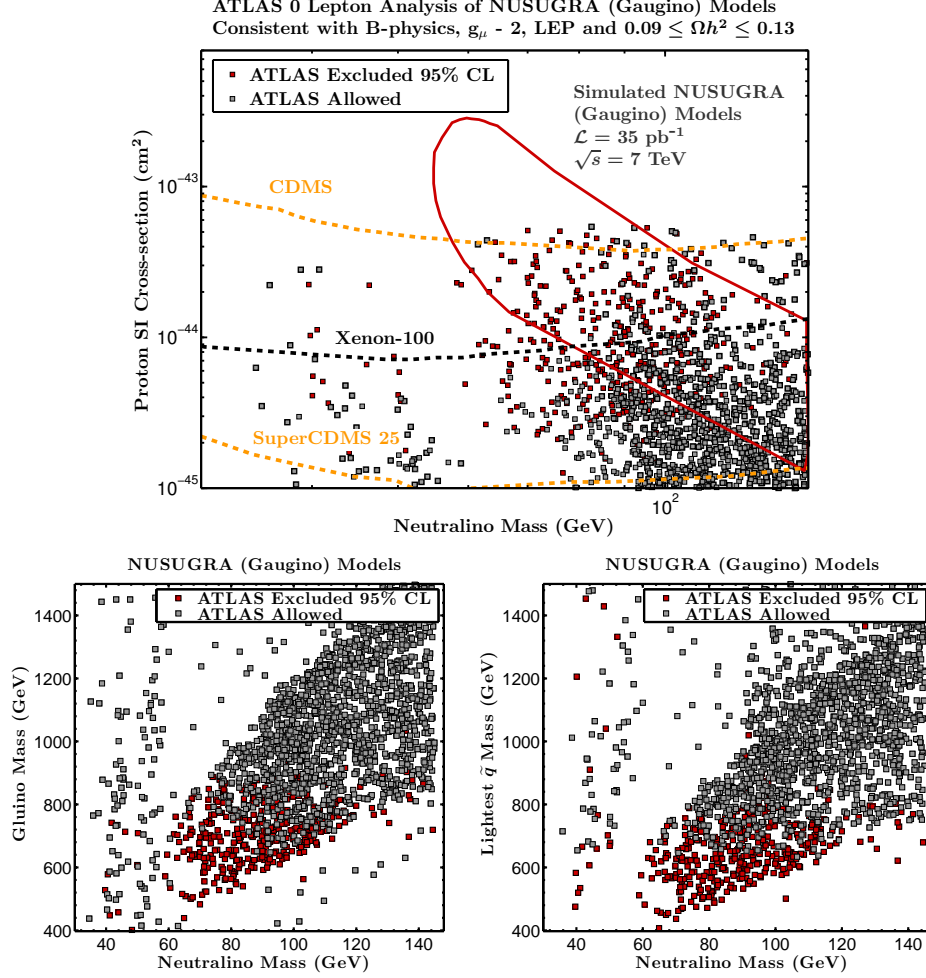


FIG. 5: (color online) Repopulation of the region depleted by ATLAS. Shown are NUSUGRA models, where the red contour is the ATLAS constrained region in mSUGRA. The non-universal gaugino models simulated (a subset of models in Fig.(4)) under the ATLAS 0 lepton cuts that are constrained by the analysis indicated by red squares. The bottom two panels show the gluino mass and the lightest second generation squark mass where we note a gluino mass as low as 400 GeV and squark masses as low as 600 GeV are unconstrained by the present ATLAS data.

gaugino masses, and most generally a combination of both as

$$M_a = m_{1/2} (1 + \delta_a) \quad (11)$$

at the GUT scale for the gauge groups  $U(1), SU(2)_L, SU(3)_C$  corresponding to  $a = 1, 2, 3$ . The ranges chosen are  $\delta_a = (-1, 1)$  with the ranges for the remaining parameters as in the mSUGRA case.

The result of the analysis is shown in Fig.(4) where we exhibit the allowed set of models over a broad range of neutralino masses which satisfy all the experimental constraints, but do not yet have the LHC SUSY search constraints applied to them. The area depleted by the LHC for the mSUGRA case lies within the red boundary and is shown for comparison. One observes that the presence of non-universalities in the gaugino sector repopulates a significant part of the region of the signature space in the spin independent scattering cross section-neutralino mass plane that is constrained by the LHC SUSY searches relative to the case of minimal SUGRA. This region of repopulation is found to produce a consistent relic density via multiple coannihilation channels.

In particular, because the chargino mass can be split from the LSP mass with non-universalities in the gaugino sector consistent with the LEP bound on the chargino mass, the low mass region below the light CP even Higgs pole, which is largely the Z-pole region, is now allowed by the relic density constraint. Thus one can have a dark matter mass as low as

$$m_{\tilde{\chi}_1^0} \gtrsim 40 \text{ GeV} \quad (\text{NUSUGRA} - \text{gauginos}) \quad (12)$$

in the NUSUGRA case, where the lower limit is higher in the mSUGRA case to be consistent with the LEP data.

The top panel of Fig.(5) gives the analysis with a focus on the 50 GeV to 100 GeV neutralino mass region where we also apply the LHC analysis as already described. From Fig.(4) and the top panel of Fig.(5), it is apparent that the gaugino mass non-universalities produce a significant repopulation of the region with models specifically in the 50 GeV to 100 GeV neutralino mass range. Also shown in the bottom two panels of Fig.(5) are the gluino mass and the lightest second generation squark mass. We note that a gluino mass as low as 400 GeV and a squark mass as low as 600 GeV are unconstrained by the present ATLAS data. Similar results are obtained when non-universalities in both the gaugino sector and the Higgs sector [46] are present. In this case the analysis gives results similar to those of Fig.(5) with a larger density of allowed models which populate the region depleted by the LHC SUSY searches.

## VI. CONCLUSION

The implications of the first SUSY analysis by CMS and ATLAS on supersymmetric dark matter are analyzed. It is found that the CMS and ATLAS constraints deplete a significant branch of the slepton coannihilation regions in the mSUGRA parameter space where dark matter can originate in the early universe while the Higgs pole region and the Hyperbolic Branch (focus point region) are not constrained. However, a large portion of the Hyperbolic Branch region is now becoming constrained by the recent XENON data. The effect of non-universalities in the gaugino masses are analyzed and it is found that a part of the region in the spin-independent cross section vs the LSP mass plane depleted by the CMS and ATLAS analysis for mSUGRA is repopulated when non-universalities are included, i.e., for the NUSUGRA case. Thus observation of dark matter in the mSUGRA region depleted by the ATLAS constraints could point to supergravity models with non-universal soft breaking.

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**Note added:** Near the completion of this work a new ATLAS analysis [49] appeared and our results are consistent with their analysis. Further, after the appearance of the work presented here, an analysis in similar spirit appeared in Ref. [50], and their overlapping results are consistent with ours. For the case of minimal supergravity Ref. [50] exhibits the NLSPs in the spin independent cross section - LSP mass plane. This is a useful technique for understanding the physical content of models in this signature space as discussed in [51, 52].

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